Epistemology & the Nature of Science: A CLASSROOM STRATEGY

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Efforts by state and local officials to enact balanced treatment laws represent attempts to displace the methodological naturalism of science with theological supernaturalism. Advocates of creation science and intelligent design (ID) also seek to wedge the supernatural into scientific explanations. Robert Pennock (2000) distills the controversy to its core features when he states, "debate [is] about truth itself and how we come to know it" (p. 40). In this article I assume methodological naturalism as a presupposition in modern science. This is in agreement with the decision handed down by Judge John E. Jones III in the Dover, Pennsylvania ID case. Citing trial testimony from well-known philosophers of science, Jones (2005) wrote, "Methodological naturalism is a 'ground rule' of science today which requires scientists to seek explanations in the world around us based upon what we can observe, test, replicate, and verify" (p. 65).

Legal challenges to the teaching of evolution as a process explicable by naturalistic causes or to exclusive reliance on naturalism in science would alter science education by redefining science. Langdon Gilkey (1985) notes that these challenges pose additional threats. First, such laws would establish a particular form of Christian religion in the science classroom. This threatens free religious life in our society as well as freedom from religion. Second, such laws attack academic freedom. States often legislate what subjects are to be taught in the curriculum, but they should not dictate which theories are to be taught within these mandated subjects (pp. 13-14).

Attacks on the nature of science should motivate us to teach not only that science adds to our body of knowledge but also to emphasize how it does this. In what follows, I set forth an interactive activity titled "Epistemology and the Nature of Science" designed for this purpose. Epistemology is the formal study of the nature and limits of human knowledge. It includes careful assessments of the limitations of the methods we employ when we make claims about what it is we know. The interactive activity helps students realize that the body of knowledge we associate with science is established using specific epistemic methods. I begin with a brief description of the format of the activity, which involves constructivist listening and the dyad. Following this, in Part I, I canvas how student responses reflect and fail to reflect major ways of knowing and their relation to science. In Part II, I use Judge William Overton's list of the characteristics of science—from the 1982 Arkansas creation trial—to focus discussion specifically on the nature of science.

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Constructivist Listening & the Dyad

I developed Epistemology and the Nature of Science as an interactive activity for use with my Grade 9 students six years ago. Currently, I use it for my Grade 8 Pre-AP Introduction to Chemistry, Physics, and Earth Sciences course and my Grade 9 Pre-AP Biology and regular Biology classes. I have also used it with adults who teach science and math for Grades 5-12 for professional development. Central to this activity are the concepts of constructivist listening and the dyad.

Constructivist listening is a process that allows one to talk without being interrupted and thereby to explore thoughts in an unimpeded manner. Talking can be as important to the learning process as listening. This is evident when teachers use questioning strategies that encourage students to talk through solutions for particular problems. Teachers often say they didn't really learn a subject in depth until they had to teach others. This may be due, in part, to the fact that teachers must talk about their subject areas. Constructivist listening is not a conversation or dialogue. Listening is really for the benefit of the speaker. It allows the speaker to explore content or feelings without being interrupted. The dyad is one structure that promotes constructivist listening. The word *dyad* means "two as one." The dyad allows two people to have equal, uninterrupted talking time. After students are paired, they are given a prompt. We follow guidelines adapted from *Ripples of Hope* (see Weissglass & Sarason, 1998, pp. 44-45).

Dyad Guidelines

- Each person is given equal time to talk.
- The listener does not interpret, paraphrase, analyze, give advice, or break in with a personal story.
- Confidentiality is maintained.
- The talker is not to criticize or complain about the listener or mutual acquaintances in his/her turn.

Epistemology & the Nature of Science: Part 1

After students are acquainted with the concepts of constructivist listening and the dyad format, they are paired together and given a 40 cm x 33 cm white board and a marker. To help them explore their thoughts, I give them the following prompt:

How do we gather knowledge?

I clarify by asking, "If you want to know more about some topic, what do you do? Where do you go?" One student records what the other brainstorms for one minute. Students then switch roles for one minute. When the students have completed the dyad, we reconstruct the ideas on the chalkboard. I ask each dyad to share one idea from its board. After they have all shared I ask if anyone else would like to add more to our brainstorming list. The confidentiality rule helps in two ways. First, it protects students from being embarrassed by the ideas they might share in the dyad. In this activity students choose what ideas they share. Second, it ensures that my next classes will enjoy a fresh approach to the exercise uncontaminated by suggestions from the previous class.

We now compare the ideas that the class has generated through the dyads with major methods of gathering knowledge recognized by philosophers: authority, empiricism, rationalism, aestheticism, and pragmatism (see Viney & King, 2003, pp. 15-18). I put these ideas on the overhead and we use this document to categorize the students' ideas. In this exercise we focus on these epistemic methods and examine them in terms of their relationship to science.

Authority

Authority is a common way to assess truth, and authorities exist in the form of books, institutions, and people. In a recent classroom sample of 59 students, 80% of the responses fit into this category. Student ideas included such examples as parents, books, the Internet, teachers, experts, and magazines. Reference to authority is used in all human endeavors; it is used in teaching, law, religion, and science. It is a convenient and efficient means of gaining knowledge, but it can also be a source of misinformation. In fact, there have been long stretches of history marked almost exclusively by reliance on authority, tradition, and revelation. Masses of people the world over are still informed and live their lives according to the dictates of such methods. There are important questions regarding this method of knowing and how it should be used. What should one believe when authorities disagree with each other? Is authority open to independent confirmation? Is it regarded as absolute? These are critical questions important to any scientific endeavor. My hope is that students come to realize that, as far as science is concerned, an authority's claims are only as secure as the scientific evidence that lies in back of them.

Empiricism

Empiricism places emphasis on experience in the acquisition of knowledge, usually with special attention to experimentation. Science prefers using numerous empirical methods through induction to discover natural patterns. Francis Bacon championed this marriage between empiricism and inductive reasoning by enumeration and is often regarded as the herald of the empirical spirit. Ruse (1999) points out that William Whewell believed the best kind of science seeks a consilience of inductions in which inductions from different areas of science are explained by the same principle (p. 58).

Empirical methods of gathering knowledge usually come in second place in our classroom exercise. In my recent student sample, 20% of responses fit into this category. Students' responses included: trial and error, experiments, and observing.

Rationalism

Rationalism, or the use of reason to gain knowledge, comes in a distant third on my students' lists. Over many classes, less than 1% of responses fit into this category. In my recent student sample, 0% of the responses fit into this category. Nevertheless, students occasionally mention logical problem solving, argumentation, and mathematical equations. Descartes is often viewed as the founder of modern rationalism, though rationalism, like empiricism, had roots in the thought of numerous Greek philosophers.

Students often use logic, but they are unaware of formal classifications, for they have rarely been introduced to them. For example, students argue by analogy—similar circumstances warranting similar conclusions—when reasoning with their parents. Matt may say, "Katie's parents let her go to the 10:00 p.m. movie if she is getting at least a B average. I have a B+ average, so I think I should be able to go to the movie." Charles Darwin used an argument by analogy when comparing artificial selection with natural selection. Artificial selection is a non-random human selection working on a random genetic variation. Natural selection is a non-random selection through differential survival and reproduction working on a random genetic variation. William Paley's argument from design is also a well-known example. Objects in the universe have the appearance of design, so they must have a designer. Darwin knew this argument and reflected upon the human eye as an example (1859/2004, pp. 156-163). He reasoned that there is great variation in eyes and that the complexity of the eye is reducible to a series of small, adaptive steps. He correctly predicted that eyes representing these steps would be found in nature.

Students also understand elementary deduction. I ask my students, if we all agree that teachers are the "best," then what must we conclude if Mrs. Klass is a teacher? Students quickly see that Mrs. Klass is the best. I ask them if complementary angles are defined as adding up to 90˚ and we know that one of two angles is equal to 30˚, can we use reason to determine the second angle? They quickly learn that in deductive arguments a premise or axiom is given to be true and this leads to inescapable conclusions. Mathematicians rely heavily upon deductive reasoning. However, deductive reasoning comes at a price. Students realize that if the axiom is not true then the conclusion is in question.

Empiricists favor inductive reasoning, for it utilizes independent lines of empirical evidence to support a common conclusion. As previously noted, Bacon suggested that science should seek patterns by constructing generalizations from numerous direct observations. For many centuries Europeans noticed that every swan they observed was white in color. Swans were considered always to be white, but then black swans were found. This simple example illustrates that induction provides only a tentative conclusion.

The hypothetico-deductive method combines deductive and inductive procedures. Deduction is used to generate specific testable hypotheses from a theory. These hypotheses are then used to make predictions. These predictions, in turn, are tested against the observations that we make. Evolutionary theorists hypothesized that whales evolved from a land mammal. Informed by this hypothesis, paleontologists make predictions concerning what type of fossil evidence may be discovered in the future. This method has enjoyed great success. The process that Charles Sanders Peirce (1955, pp. 150-156) called abduction complements the hypothetico-deductive method, but works in the opposite direction: Here we look for hypotheses that explain the observed patterns. Early paleontologists noticed that fossils indicate that life has changed over time. Competing hypotheses, which attempted to explain this pattern, included catastrophism and evolution. Note that it matters not whether data are collected from the past or the present, but whether the data stand in the proper relation to the hypothesis.

Aestheticism

In the many years I have done this exercise, only two classes have included beauty as a method of gaining knowledge. I let students know that aestheticism is not necessarily beauty in the usual physical sense. DNA is an elegant structure. Watson (1968) reports that it was said of the double helix model of DNA that it was, "too pretty not to be true" (p. 134). In philosophy, math, and science, one form of aestheticism may be represented by Ockham's Razor set forth by William of Ockham in the 14th century; simplicity is an aesthetic preference. In modern terms simple solutions are better or more aesthetic. Alfred North Whitehead's words are the core of wisdom on Ockham's razor, "Seek simplicity and distrust it" (Whitehead, 1971, p. 163). The Greek ideal of aesthetic perfection was balance and symmetry. Copernicus and others were led by this ideal to posit circular orbits for the planets. No one using the Greek ideal of beauty would have predicted Kepler's elliptical orbits. The ideal of beauty is subject to revision.

Pragmatism

According to the American psychologist-philosopher William James, pragmatism is both a method for discovering what is true and a theory of truth (James 1907/1943, pp. 65-66). As a method, pragmatism is empirical for it appeals only to experience. Both the method and the theory of truth emphasize the dynamic, mutating, growing nature of the human intellectual enterprise. James (1910/1978) asked rhetorically, "What has concluded, that we might conclude in regard to it?" (p. 190). For James, there are always new methods, new instruments, and new truths that were not apprehended in previous generations. He argued that the world is an open-ended process so there is no final once-and-for-all conclusion. What we take as true, according to James, may be only as justified as it can possibly be in a given context. Tomorrow the beliefs about which we are certain today, that we act on today, that we live by today, may be replaced. A surgical procedure that is accepted in a given period may be replaced by something unexpected resulting from the development of a new instrument or new views on the causes of disease. I ask my students if they would like to go to a dentist who uses tools and practices from the turn of the century or one who uses the knowledge gained up to the present. American industry has always had a pragmatic basis because there is both value and profit in utility and workability. Cost/benefit analysis used in evaluating the acceptability of new technologies, such as medications, may also serve as an example. A deeper grasp of pragmatism encourages epistemic humility because we realize that the claims we make are provisional.

There are other methods of obtaining knowledge such as consensus and vividness of experience. We briefly explore these methods. I ask students if the sun comes up every day. They all say yes, that is what they experience and it is vivid; however, it does not come up every day, rather, the Earth rotates. Because they are members of a democratic society, students are aware of the limitations of the consensus model. They also seem to realize that getting at what is true is problematic. The majority may be wrong.

Epistemology & the Nature of Science: Part II

Again we use the dyad format and white boards to explore the following prompt:

What is Science?

Students and even adults with whom I have worked often run out of things to say during this dyad, even though it lasts only one minute. If they run out of things to say, they must remain silent until the minute is complete, preserving equal time for each talker. After gathering their ideas on the chalkboard I let them know that there are many different views about how science gathers knowledge. Common among the students' lists are content specific disciplines within science such as the study of chemicals, life, and the solar system. Science as a process is usually represented by observation and experiment. In my recent sampling, 0.8% of the responses represented science as a process. The data I have collected indicate that my Grades 8 and 9 students overwhelmingly think of science as a body of knowledge. While it is true that science strives to develop a unified system of knowledge, it is an understanding of its epistemic methods that is crucial for grasping how science works. In the past I have compared student views with those of Karl Popper, Thomas Kuhn, and the characteristics of science as defined by the *1982 Rev. Bill McLean et al. v. Arkansas BOE (act 509)* which tested a balanced treatment law. I have refined the activity to explore only the characteristics of science as defined by the above court case. This legal definition is well suited for my purposes because it is informed by and reflects the views of scientists, philosophers of science, and science educators.

Judge Overton, writing for the 1982 case, listed five characteristics of science:

1. It is guided by natural law.
2. Explanations are in reference to natural law.
3. Hypotheses are testable against the empirical world—science is public knowledge.
4. Conclusions are tentative; there is no truly final word in science.
5. Theories and hypotheses are falsifiable (Overton, 1984, p. 380).

Let us comment briefly on each of these characteristics. The students explore how these characteristics fit with the ways we gather knowledge.

Science Is Guided by Natural Law

Science limits itself to an exploration of the natural world, which (at least for condensed matter) operates in a regular, predictable manner based on identifiable or potentially-identifiable forces. According to Pennock, science is "agnostic" since the question of the supernatural is outside the boundaries of its method of investigation (2000, p. 337). Coyne (2005) rightly observes, "The gold standard for modern scientific achievement is the publication of new results in a peer-reviewed scientific journal" (p. 32). Furthermore, apart from reviews of the literature and purely exploratory research, articles should put forth positive evidence, which can be tested by the scientific community. Working scientists around the world represent diverse cultural and religious backgrounds; however, as scientists, they are constrained by empirical evidence. It is important to note that there is a difference between professional science and popular science. Scientists are allowed to explore their own beliefs and speculations within popular venues, but such views might not be accepted in scientific journals. For example, Richard Dawkins is militantly atheistic, but his views on religion would never pass peer review in a science journal. Students and the general public may develop misconceptions about the nature of science if they are not aware of this distinction.

Scientific Explanations Reference Natural Law

If we are guided by natural law in science, it follows that our explanations must be in reference to natural law. If one's car breaks down or one feels ill, one reasonably expects a naturalistic explanation. An animistic explanation of car problems would be ludicrous. If a mechanic claims that demons were causing engine problems we would be justified in finding a new mechanic. A reliable mechanic adopts methodological naturalism. "Your problems," says the mechanic, "could be in your battery, electrical system, starter, or alternator and I can run tests to identify the exact cause." Whether the subject is a car, a flashlight, physical health, mental health, the weather or an earthquake, our society is usually scientific in preferring naturalistic explanations that can be independently verified.

Scientific Explanations Are Testable Against the Empirical World

Scientific ideas are based upon naturalistic explanations and are thus empirically verifiable. Scientific knowledge is public knowledge. For example, predictions can be derived from the theory of evolution that different organisms have lived in different temporal intervals. This is a prediction that has been overwhelmingly confirmed by examining the history of the Earth as it is revealed by the fossil record. Predictions can also be derived that organisms would look less like those of the present day as you move back in time through older layers. This again is a testable prediction and ironically, first observed by nineteenth century creationists. There are also predictions that the organisms on islands off major coasts would be closely related to species on the mainland. Furthermore, the fossils found in these locations should be related to present day organisms. These biogeographical patterns in time and space are predicted and are testable. Even more significant is the fact that scientists from different religious and cultural backgrounds can come to very close agreement on these historical patterns. Kenrick and Davis (2004) observe, "Modern science has dropped the mythological and theological in favor of explanations couched in terms of natural causes. This approach is called methodological naturalism, and its results have achieved an unprecedented degree of corroboration and acceptance across cultural divides" (p. 205). We accept scientific theories only when they make useful and dependable predictions about the natural world that can be independently confirmed empirically. Furthermore, according to Ruse (2005), "... branches of science strive to be internally coherent and externally consistent with other areas of science" (p. 35). As we uncover our curriculum during the year, we talk about the historical development of specific theories in science. Students can see the shaping of ideas through empirical methods. Students also come to understand that the experiences of which science is most sure are those that have withstood numerous independent empirical verifications.

The Conclusions of Science Are Tentative

In science no one can claim to have the final word. One might say that truth in science is not spelled with a capital T. Scientific explanations are open to review in the light of new evidence. The history of science is replete with examples. The tentative nature of scientific explanations positively reinforces a healthy skeptical habit of mind. According to Jonathan Rauch (1994), "At the bottom of this kind of skepticism is a simple proposition: we must all take seriously the idea that any and all of us might, at any time, be wrong. Taking seriously the idea that we might be wrong is not exactly a dogma. It is, rather, an intellectual style, an attitude or ethic" (p. 45).

The tentative nature of science fuels skepticism about putative absolute truths handed down by authority. If everyone must be open to having their ideas checked, then doubt and curiosity become valued. We take for granted the fact that science has institutionalized curiosity, but in the past curiosity about certain things was considered idle and sinful. Curiosity as a sin provided a moral argument against certain knowledge-gathering methods, which included, but were not limited to, philosophy, mathematics and scientific inquiry (Harrison, 2001). Dr. Stephen Thompson, a chemist at Colorado State University, advocates teaching students to always ask, "How do you know that?" The question encourages curiosity, skepticism, and demands supporting evidence. Skepticism, like curiosity, was once regarded as a sin, but in scientific epistemology, skepticism is a virtue.

The tentative nature of scientific knowledge should encourage students to preface their solutions with phrases like, "The evidence supports ... ." "The best interpretation seems to be ... ." "This represents the best thinking at this time ... ." Stephen Jay Gould (2000) would call the very essence of science a method devised to undermine proof by authority. We must be vigilant for the tentative nature of science cannot be overstated, lest we forget and turn scientific methodology into an empirical myth dominated by authority and dogma (p. 31).

Scientific Hypotheses Are Falsifiable

According to the eminent philosopher of science, Sir Karl Popper (1935/1959, pp. 40-44), scientific hypotheses and theories are falsifiable. Philip Kitcher (1982) states this same idea more memorably, "Science can succeed only if it can fail" (p. 45). The concept of a supernatural intelligent designer is not a scientifically testable assertion and is therefore not a scientific explanation. Successful scientific ideas are empirically testable and have withstood numerous attempts to debunk them.

It is important for scientists to speculate freely and be creative; however, in the end it is an empirically based decentralized checking process that determines whether or not these ideas make useful and dependable predictions. Alfred Wegener (see Hay, Nehru & Wiswall, 2003, pp. 20-35) thought "outside the box" and concluded that continents had drifted over time, but he had no testable method for how continents could move and so his idea was marginalized. In the 1960s the evidence for seafloor spreading became empirically powerful and convincing. Wegener's ideas then became a part of plate tectonic theory.

Summary & Challenge

According to Popper (1935/1959, p. 44), the final claim to objectivity in science is that it is a collective enterprise where any individual's views are subject to criticism by others. One might say that there is freedom of belief and speech in science, but not freedom of knowledge. The reason I think scientific methodology is so powerful is because of its empirical ruthlessness. Authority and expertise are used in science, but they are open to being checked. Philosophically, Einstein resisted the ideas of quantum mechanics saying that, "God does not play dice with the world" (Clarke, 1971, p. 340). Yet, the empirical evidence has allowed belief in indeterminacy to flourish in physics. Darwin doggedly stood by his theory of evolution by natural selection even though the scientific community did not yet know the mechanisms of heredity. His speculation that when this mechanism was better understood it would support his theory was born out by empirical research. It is important for our students and the general public to understand that in science no one has the final word and independent empirical testing is the trump card for knowledge gathering.

If you want to believe the Earth is at the center of our planetary system, that the entire fossil record was created from a worldwide flood, or that gaps in human knowledge about the natural world are evidence for the supernatural, that is all right. If, however, you want your beliefs recognized as scientific knowledge you must be open to empirical tests. If your beliefs do not stand up to the empirical evidence, they will not be included in scientific texts. Indeed, the intellectual community may not even take them seriously (cf. Rauch, 1993, pp. 116-117).

Julian Weissglass, Professor of Mathematics at the University of California-Santa Barbara, told me that the essence of leadership is taking responsibility for something that matters to you. If science and its methodologies matter to you then I challenge you to make them a central theme to your science instruction. Science obviously matters to those of us who teach it. Yet, the methodological naturalism on which science is based is continually called into question by creationists and proponents of ID. It follows that those who care about science have a responsibility to provide a deeper understanding of the epistemological grounds on which it rests. I hope that this article makes a small contribution in this direction.

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